Dynamic Stiffness Properties of Micropile Foundation

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ABSTRACT

Presented here is a verification of the effectiveness of a micropiles used as a measure to improve foundation dynamic behaviors, when compared with a existing pile foundation in soft soil. In this study, the dynamic analyses of group of piles were conducted with the soil-pile interactions considered, and the effects on dynamic stiffness of pile foundation were investigated numerically, including axial, lateral and rocking components, due to different pile distribution, pile diameter as well as soil conditions. The numerical computation is conducted by the finite element method for an axisymmetric model under axisymmetric/anti-axisymmetric loading conditions. As a results, the optimal selection is proposed to get micropile techniques more effective than conventional retrofit methods such as footing extension and ground improvement in resolving difficult site conditions.

1. INTRODUCTION AND BACKGROUND

Some small diameter drilled and grouted piles have been used throughout the would for various purposes, which can be expected to withstand axial and/or lateral loads, and many serve as one component in a composite soil/pile mass or a small-diameter substitute for a conventional piles. It is very important that this type of piles are installed with methods to cause minimal disturbance to structure, soil and environment, and then differentiates them from related piling techniques. The development of such small diameter piles, including the concept, design method and construction, has resulted in so-called micropiling technology, that is generally under 300 mm in diameter and is installed using rotary drilling and grouting techniques. As the foundation support elements in static and seismic situations as well as in situ reinforcement of slop and excavation stabilization, the micropiling technology has advanced rapidly since the mid-1980s, because of their high axial load-holding capacity and their ability to be installed in difficult locations and geologies as well as their minimal disturbing surround soil mass [2]. Up to now, the lightly loaded structures such as town house development, residential houses, warehouses, light industrial buildings, machine bases, marina jetties and many other examples can be supported on micropiles. But, recently, these piles often provide technically viable solutions for higher loaded foundations in restricted areas, such as the widespread use in urban areas and in seismic retrofit projects in U.S. and Japan. Especially, in the highway bridge foundation reinforcement, the micropiles have been put in practice very well [1].

The micropiles can be classified based on its functions, i.e., as structural support or as in situ soil reinforcement, and the method of grouting, which is generally the most sensitive in construction control over grout/ground bond development and thereby over pile capacity. Of the functional aspects, the groups of micropiles for structural support are designed to accept directly the applied loads and so act as substitutes for, or special versions of, more traditional pile types. In other words, except the construction process of micropiles, there should be no difference on the soil-pile interaction analysis method. Even on the construction, the micropiles can also be considered a small-diameter subset of cast-in-place replacement piles. However, the "small diameter" would mean small cross-sectional area, and then low structural capacity, while the high capacity steel micropiles would play another part in the behaviors of foundation. Herein, focusing the attention on the elastic load capacity of such soil-pile systems, the linear analysis by the finite element approach with use of transmitting boundary at the side of the ground model is conducted and the dynamic stiffness of foundation is presented.

From the convenience of treating the 3-dimensional soil-pile interaction, the axisymmetric three dimensional model is employed for axisymmetric and anti-axisymmetric harmonic loading on the foundation.

In seismic design point of view, the Kobe quake has forced administration in Japan to modify their seismic resistant standards in concept and design codes, and many of structures become lack of seismic resistant capacity in the quake motion of same intensity. For example, the bridge structures including railway and highway transportation have to be retrofitted with steel jacketing techniques for the pier columns. In this case, the foundation structures will withstand more seismic input energy, and the reinforcement of foundations in seismic situation become very important associated with the earthquake resistant capacity improvement of superstructures, as interpreted in Fig. 1. Normally, the foundation structure behaves ductile, even if the pile members are possible to be damaged during early stage of seismic input. To achieve better bridge foundation anchorage in the seismic upgrade associated with the retrofitting of bridge piers, and to avoid the earlier damage of foundation members than the members in superstructure, the micropiles should be expected to be more effective because of its high ductility. Such considerations mentioned above will be verified in detail in further nonlinear soil-pile interaction studies.

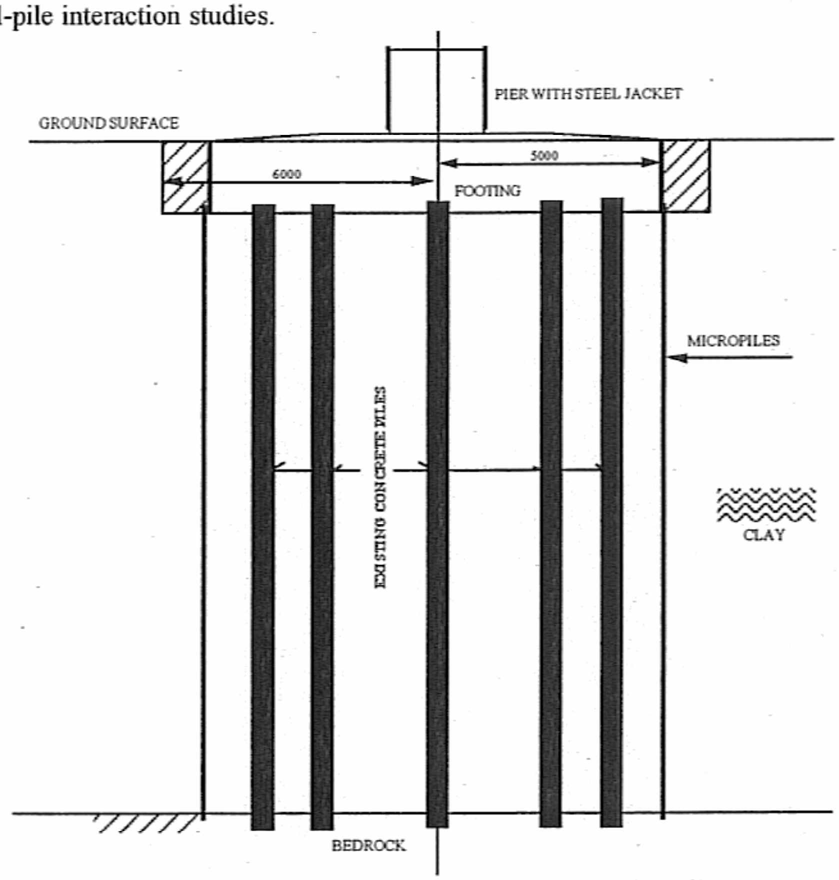


Fig. 1 Foundation with existing piles and micropiles

2. BASIC EQUATIONS FOR RING PILE DYNAMICS

Applying the substructure concept to the analysis of piles and nearby soils, one may superimpose the pile stiffness on to that of the soils for the interaction system. However, since the free field is used for the latter analysis, due care should be taken to evaluate the reduced piles stiffness by that of soils. The same holds true in assembling the mass matrix as well. The hysteric damping effect is taken into account for the internal energy dissipation in addition to the radiating wave horizontally towards infinity. The axisymmetric arrangement of piles is assumed for the model. Pile tips are built in to a presumed rigid bedrock and the pile heads are perfectly connected to a rigid body footing. The infinitely extending side region of the soil is replaced by the so-called transmitting boundary element based on the surface wave propagation (generalized Rayleigh and Love waves) in the concerned layer Only some essence of the formulation is presented here from the work by Kausel and Roesset, 1975; Takemiya, 1986, Takemiya and Jiang, 1993 [3], to make the procedure clear.

In case of the piles plan view of concentric layout, the pile-soil-pile interaction may well be interpreted by the Fourier series expansion for the response depiction. Normally, a limited Fourier terms are used so as to meet the displacement compatibility for the footing motion. Specifically, for the vertical motion of a rigid footing, the n=0 axisymmetric term; for the coupled sway along x-axis and rocking motion about y-axis of a rigid footing, the n=1 symmetric term about the x-axis.

The FEM modeling is performed by solid elements for the nearby soil and the beam elements for the piles. The interaction between these elements are taken into account at the nodes only, demanding the nodal displacement compatibility and the corresponding forces. The internal forces of piles is presumed to follow as mentioned above along the azimuth around the footing axisymmetric center.

The governing equation of motion of nearby soils is established in the cylindrical coordinates by expanding displacements and the forces into the Fourier series along circumferential direction.

$$U(r,\theta,z) = \sum_n H_n^s(\theta)U_n^s(r,z) + \sum_n H_n^a(\theta)U_n^a(r,z) \qquad (1)$$

$$P(r,\theta,z) = \sum_n H_n^s(\theta)P_n^s(r,z) + \sum_n H_n^a(\theta)P_n^a(r,z) \qquad (2)$$

in which the Fourier amplitude vectors $U_n(r, q, z)$, $P_n(r, q, z)$ with superscript "s" stand for symmetric Fourier components and "a" for anti-symmetric ones, the displacement and force vectors are

$$U(r,\theta,z) = (\ u_r \quad u_\theta \quad u_z\ )^T \qquad (3)$$

$$P(r,\theta,z) = (\ p_r \quad p_\theta \quad p_z\ )^T \qquad (4)$$

and the variation $H_n(q)$ along the circumferential direction is prescribed by the diagonal matrices of

$$H_n^s(\theta) = diag.\ (cos\ n\theta \quad -sin\ n\theta \quad cos\ n\theta\ ) \qquad (5.a)$$

$$H_n^a(\theta) = diag.\ (sin\ n\theta \quad cos\ n\theta \quad sin\ n\theta\ ) \qquad (5.b)$$

The finite element discretization is conducted by the conventional isoparametric assumption, leading the governing equation for the Fourier amplitudes as

$$\left[-\omega^2 M^{s(a)}_{soil,n} + i\omega C^{s(a)}_{soil,n} + K^{s(a)}_{soil,n}\right] U^{s(a)}_{soil,n} = P^{s(a)}_{soil,n} \qquad (6.a)$$

or

$$D^{s(a)}_{soil,n} U^{s(a)}_{soil,n} = P^{s(a)}_{soil,n} \qquad (6.b)$$

where $D^{s(a)}_{soil,n}$ defines the dynamic stiffness of $D^{s(a)}_{soil,n} = -\ \omega^2 M^{s(a)}_{soil,n} + i\omega C^{s(a)}_{soil,n} + K^{s(a)}_{soil,n}$ with $M^{s(a)}_{soil,n}$, $C^{s(a)}_{soil,n}$ and $K^{s(a)}_{soil,n}$ being the associated mass, damping and stiffness matrices, respectively; ω is the frequency concerned.

The pile's equation, on the other hand, needs rotation angles in addition to displacements for describing the deformation and the associated forces including moments.

$$U(r,\theta,z) = (\ u_r \quad u_\theta \quad u_z \quad \Phi_r \quad \Phi_\theta \quad \Phi_z\ )^T \tag{7}$$

$$P(r,\theta,z) = (\ p_r \quad p_\theta \quad p_z \quad M_r \quad M_\theta \quad M_z\ )^T \tag{8}$$

The corresponding Fourier expansion in this case becomes as

$$\begin{aligned} \begin{Bmatrix} u(r,\theta,z) \\ \Phi(r,\theta,z) \end{Bmatrix} &= \sum_n \begin{bmatrix} H_n^s(\theta) & \\ & H_n^a(\theta) \end{bmatrix} \begin{Bmatrix} u_n^s(r,z) \\ \Phi_n^s(r,z) \end{Bmatrix} \\ &+ \sum_n \begin{bmatrix} H_n^a(\theta) & \\ & H_n^s(\theta) \end{bmatrix} \begin{Bmatrix} u_n^a(r,z) \\ \Phi_n^a(r,z) \end{Bmatrix} \end{aligned} \tag{9}$$

$$\begin{aligned} \begin{Bmatrix} p(r,\theta,z) \\ M(r,\theta,z) \end{Bmatrix} &= \sum_n \begin{bmatrix} H_n^s(\theta) & \\ & H_n^a(\theta) \end{bmatrix} \begin{Bmatrix} p_n^s(r,z) \\ M_n^s(r,z) \end{Bmatrix} \\ &+ \sum_n \begin{bmatrix} H_n^a(\theta) & \\ & H_n^s(\theta) \end{bmatrix} \begin{Bmatrix} p_n^a(r,z) \\ M_n^a(r,z) \end{Bmatrix} \end{aligned} \tag{10}$$

The governing equations of piles for the Fourier amplitudes can be obtained by the conventional finite element procedure based on the beam theory and are expressed in a similar form with Eq.(6). Therefore, for respective Fourier terms, the nodal displacement compatibility and the nodal force equilibrium constitute the pile and soil interaction equation .

$$(D_n^{s(a)} + R_n) U_n^{s(a)} = P_n^{s(a)} \tag{11}$$

in which $D_n^{s(a)}$ defines the total dynamic stiffness of pile-soil system within finite element domain, and the R_n impedance matrix of the lateral infinite soil domain on transmitting boundary that is estimated through three dimensional thin layer element method.

The foundation motion U_F at a reference node (master node) is expressed in the Cartesian coordinates. The transformation is therefore executed through $T_n^{s(a)}$, as a rigid body to the displacements at nodes of the soil-foundation interface (slave nodes). Thus, Eq.(11) results in

$$P_{s,n}^{s(a)} = (D^{s(a)} + R)_{c,n} U_{s,n}^{s(a)} = (D^{s(a)} + R)_{c,n} T_n^{s(a)} U_F \tag{12}$$

in which $(D^{s(a)}+R)_{c,n}$ defines the dynamic stiffness after condensing out the degrees of freedom in $(D^{s(a)}+R)_n$ except those at slave nodes; $P_{s,n}^{s(a)}$ is the corresponding condensed driving force.

Furthermore, the soil-foundation interface nodal forces including the moment in the cylindrical coordinates are also transformed into those for the master node of the foundation in the Cartesian coordinates .

$$P_F = \sum_n \alpha_n (T_n^{sT} P_{s,n}^s + T_n^{aT} P_{s,n}^a) \tag{13}$$

with $\alpha_n = 2\pi$ for n=0 and π for n>0. It follows from Eqs.(12),(13) that we get the equilibrium equation of the footing as

$$\Big[\sum_n \alpha_n\{ T_n^{sT}(D^s+R)_{c,n}T_n^s+T_n^{aT}(D^a+R)_{c,n}T_n^a\} \qquad (14)$$

$$-\,\omega^2 M_F\Big]U_F = P_{sup} + P_g$$

in which P_g is the effective input force due to the kinematic interaction with soils through seismic incidence and P_{sup} is the force to exert directly from the superstructure.

For incident SV plane wave, the displacement at base nodes is defined as

$$u_{b,n}^{s(a)} = A\,T_{b,n}^{s(a)}\,u_0 \qquad (15)$$

$$u_0 = (\cos\gamma \quad 0 \quad \sin\gamma)^T$$

$$A = e^{ik_s\cos\gamma\, z_0}$$

where u_0 is unit displacement vector, and γ is incident angle, k_s is wave number z_0 is the vertical coordinate of the base nodes. The transform matrix $T_{b,n}^{s(a)}$ can be determined by introducing Bessel functions to represent the plane wave propagation. Thus the free-field displacements and forces on lateral transmitting boundary can be calculated by one dimensional model appropriately, and then the effective input motion or force to foundation are determined.

3. MODELING AND RESULTS

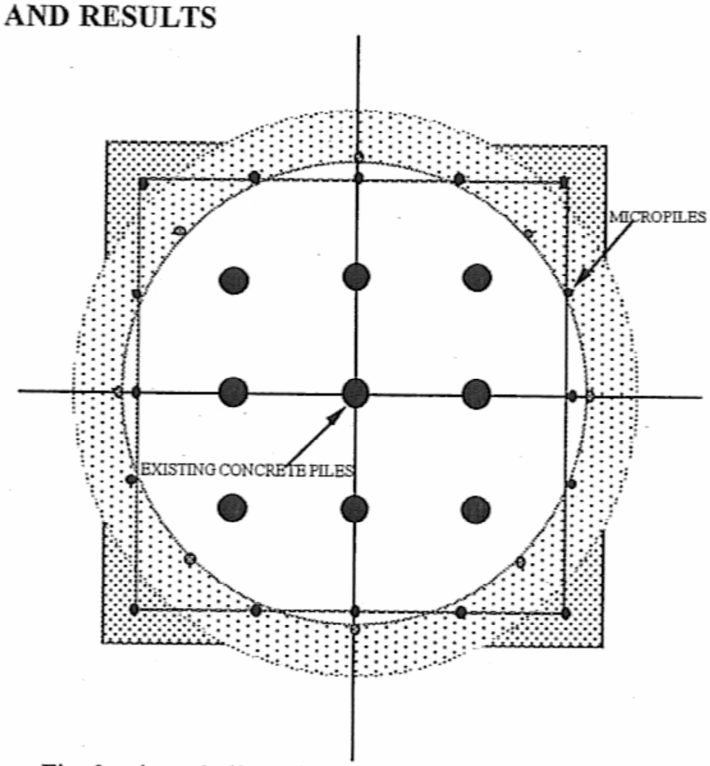


Fig. 2 Actual pile and equivalent ring piles distribution

Used for analysis is a bridge pile foundation as drawn in the Fig. 2, with 5 by 5 meters square and 1.7 meters thick footing, in addition to nine concrete piles in the diameter of 50 centimeters. After the reinforcement of bridge pier, the foundations become relatively weak and the damage energies are expected to concentrate to foundation under the seismic loading, so how to improve the foundation capacity to resist the loading and defomation has become very important. For such existing structural foundation, almost no enough vertical space and horizontal spread are offered for construction, so the micropiles are of a good solution. Selected here is a steel pipe pile drilled into soil along the edge of existing footing and grouted to footing extension.

The presence of a soft clay layer with thickness of 15 meters on the bedrock is considered to affect the dynamic behaviors of pile foundation, the profile of which is given as Fig. 3. The soil-pile interaction should also be considered to influence the efficiency of micropiles, so the finite element domain would include the beam element (for piles) and solid element (for soils), boundary conditions of rigid footing and transmitting boundary in lateral soil layer. All analyses are conducted in the frequency domain up to 10 Hz. Since our primary focus is placed on the dynamic stiffness properties of foundation, the response of the near soil field as well as the footing when micropiles installed will be discussed at next paper.

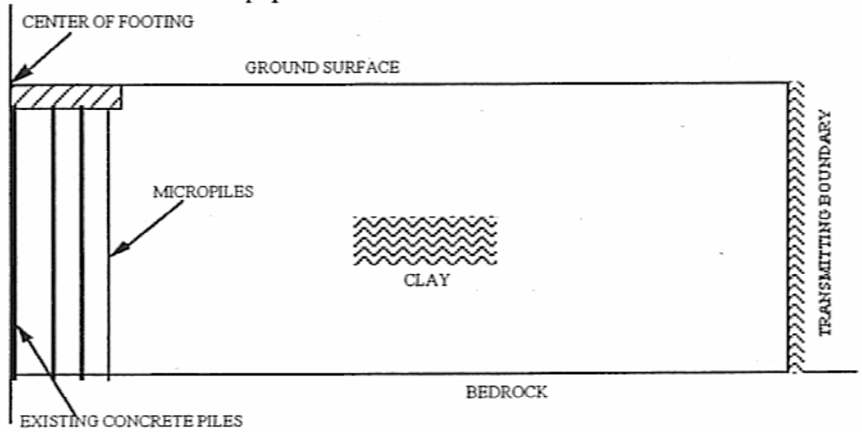


Fig. 3 Finite element domain for axially symmetrical 3-dimensional analysis

To investigate the soil-pile interaction, three types of soil (Vs=100 m/s, 200 m/s, 300 m/s), as well as three types of drilled steel pipe micropiles (D= 100 mm, 200 mm, 300 mm) with the same 10 mm thick wall are considered respectively. The ends of micropiles are drilled to bedrock and the tops of them are cast into extended reinforced concrete pile cap. All the case studies are described in Table 1, which can be allocated the first number denoting the soil condition, and the second denoting the pile diameter. For example, the micropile of 100 mm in diameter drilled in soil with shear velocity of 100 m/s, is referred to as case11. The letter r means the real part (line) and i image (dot line). Two pile distributions are introduced, the equivalent number of ring pile is 8 and 16 respectively.

Table 1 Case for studies

D: diameter of micropile, Vs: shear wave velocity in soil

pile diameter / soil conditions	no micropiles	D=100 (mm)	D=200 (mm)	D=300 (mm)
Vs=100 m/s	case10r, or i	case11r, or i	case12r, or i	case13r, or i
Vs=200 m/s	case20r, or i	case21r, or i	case22r, or i	case23r, or i
Vs=300 m/s	case30r, or i	case31r, or i	case32r, or i	case33r, or i

Figs. 4. show the horizontal, vertical and rocking components of foundation impedance. Normalized presentation is made by dividing the components by the corresponding absolute one of existing foundation, so it is only a ratio with respect to the existing foundation. From Figs. 4 (a-1) and (b-1) for horizontal stiffness, which is most sensitive on the response due to the vertically incident shear wave, one can note that a) the spectrum vibrates obviously for different range of frequency, that depends mainly on the ground horizontal vibration characteristics; and b) the foundation with micropile reinforcement becomes 20% higher in stiffness than existing one within low frequency

range and shows insignificant changes in high range of frequency; c) the image parts with miropiles show larger values as the frequency increased than without, pointing out the more energy dispersions in foundation due to the installation of micropiles; d) almost no difference is found in different micropile diameter and amount, being of no consequence as the structural members with micropiles. However, for the vertical and the rocking stiffness (Figs. 4 (b-1), (b-2), (c-1), (c-2)) more effectiveness can be expected when micropiles installed, and difference found in various type of pile diameter and distribution. Furthermore, because of the coupling of horizontal and rocking motion, the capacity to resist horizontal loading would become more powerful.

Sometimes, the underlying soil conditions are unsuitable for seismic loading and need improvement and thereby the efficiency of this type of small diameter pile will depend primarily on the geotechnical conditions on site. So in this study, another two types of soil conditions were simulated. Following results are the results for improved soil condition, with shear velocity of 200 m/s (Figs. 5) and 300m/s (Figs. 6), which indicate the same considerations as Figs. 4 qualitatively. It is very interesting to note that as the ground is improved the multiple of stiffness increase will concentrate gradually to 1.2 in horizontal component, 1.3 in vertical, and 1.6 in rocking, resulting in the extended footing playing more effective role in foundation reinforcement instead of the micropile diameter or their distribution

4. CONCLUSIONS

As an approach of foundation seismic resistant improvement, the micropiles are widely used because mainly of their convenience for construction and their better cost performance. From the point of view of dynamics, such small diameter micropiles show no significant improvement of foundation stiffness in the higher frequency range under 10 Hz, but the effectiveness is evidence in static or in low frequency range under about 5 Hz. On the other hand, such high strength steel piles will share more damage energy during seismic input and are expected to improve the dynamic behaviors of foundation. As has been indicated, the site conditions should affect the soil pile interactions in general and the micropile system could be more powerful in soft ground site from the numerical results in this case studies.

The numerical analysis can be conducted on the axisymmetric 3-dimensional model under the axisymmetric and anti-axisymmetric exciting on the rigid massless footing or the incident seismic wave motion, so not only the dynamic stiffness of foundation but also nearby soil response in the various frequency range could be investigated, as indicated in the Equ. (15). However, in our opinions, the soil responses, even if the responses of superstructure on such micropile foundations would show no significant difference from existing foundation.

In fact, another important aspect of installing a micropile should be to improve the performance of foundation when in the ultimate limit state, to better the ductility of existing foundation members and to delay the damage of foundation from superstructure, not to stiff the foundation in elastic status only. This issue would be discussed in next paper by nonlinear analysis of soil-pile interaction system with micropiles installed.

REFERENCES

[1]. T. Kisisita, et al (1998), Seismic Retrofitting of Existing Structural Foundation by High-Capacity Micro Piles, Journal of Fujita Technical Research Institute, No.34, 1-6

[2]. Donald A. Bruce, Al F. Dimillio and Ilan Juran (1995), A Primer on Micropiles, Civil Engineering, ASCE, Vol. 65, No. 12, 51-54

[3]. H. Takemiya and J. Jiang (1993), Wave Impeding Effect by Buried Ring Block for Pile Foundation, Journal of Structural mechanics and Earthquake Engineering, JSCE, Vol. 10, No. 3, 149s-156s

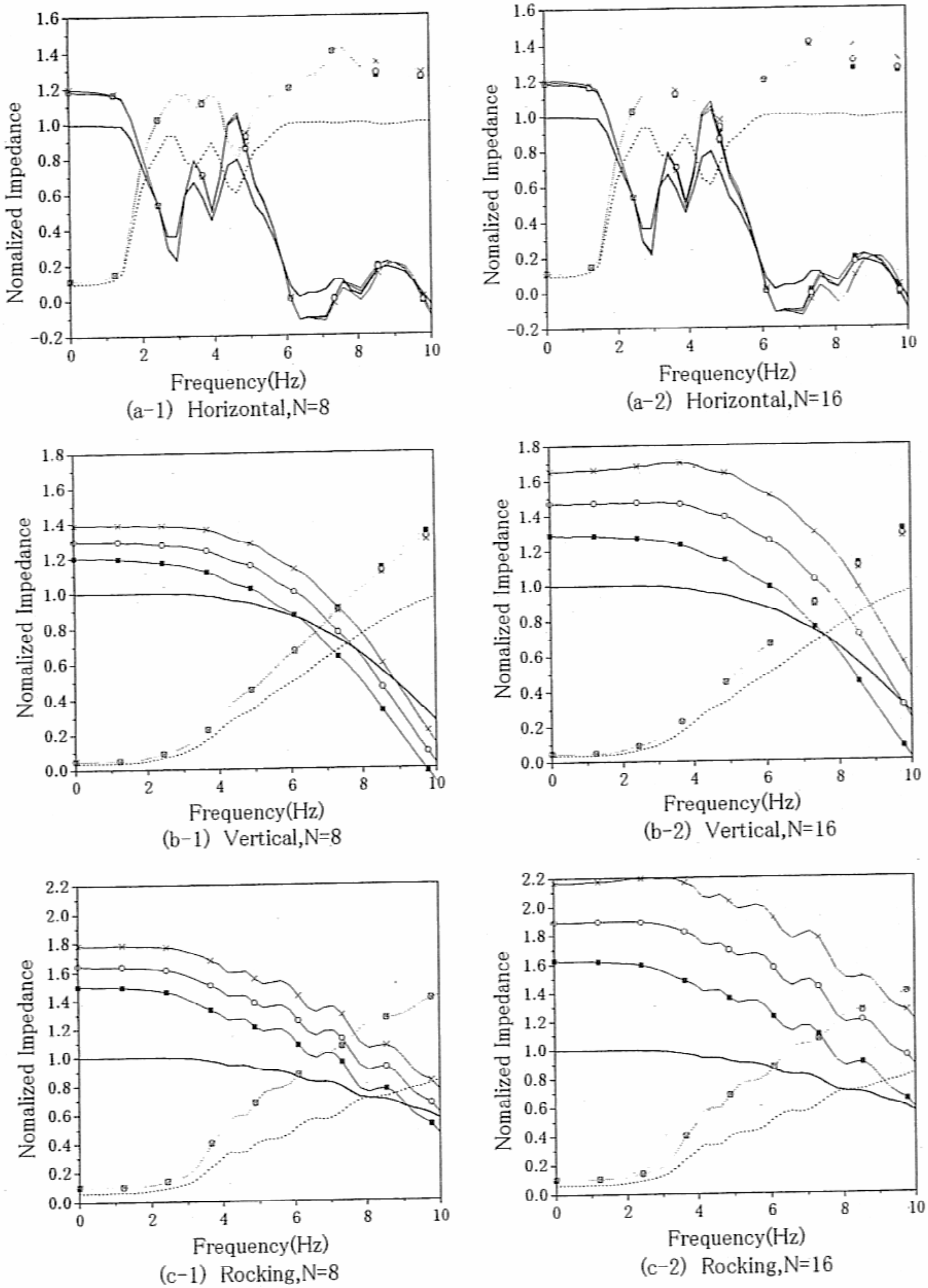
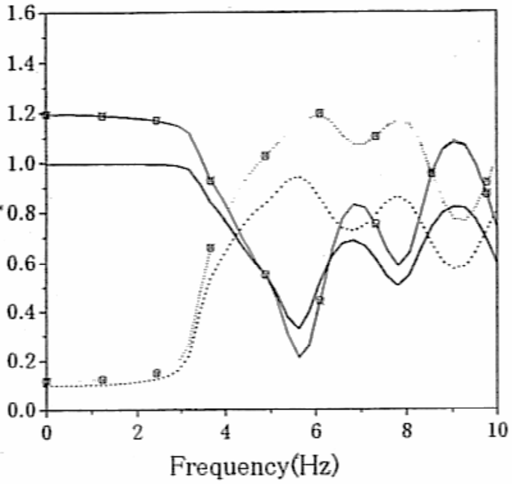
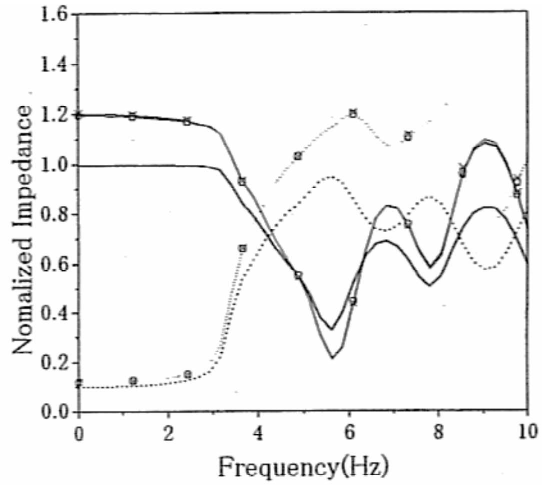


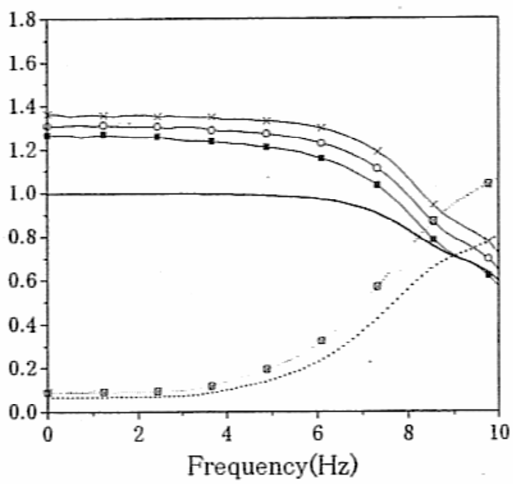
Fig.4 Dynamic stiffness of case10,case11,case12,case13 for 8 and 16 micropiles



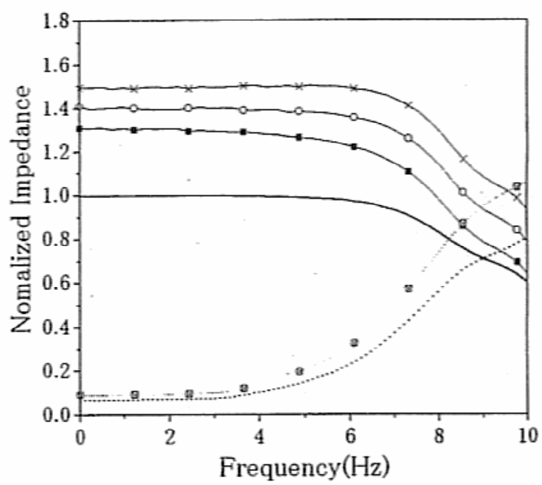
(a-1) Horizontal,N=8



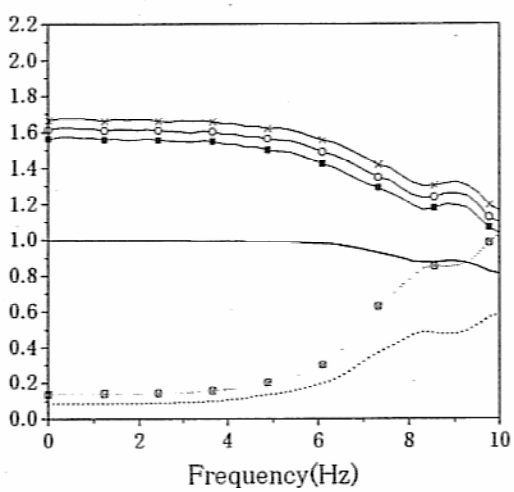
(a-2) Horizontal,N=16



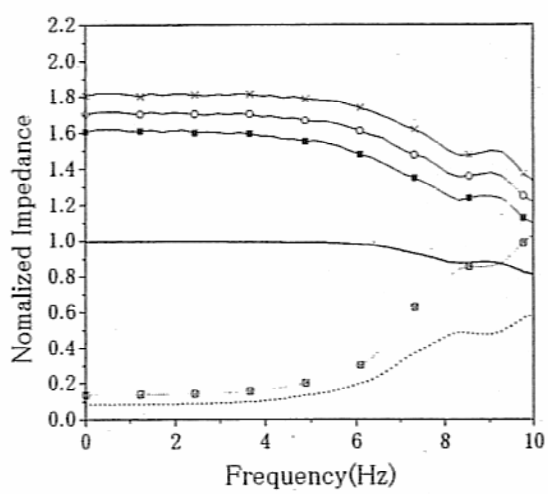
(b-1) Vertical,N=8



(b-2) Vertical,N=16



(c-1) Rocking,N=8



(c-2) Rocking,N=16

Fig.5 Dynamic stiffness of case20,case21,case22,case23 for 8 and 16 micropiles

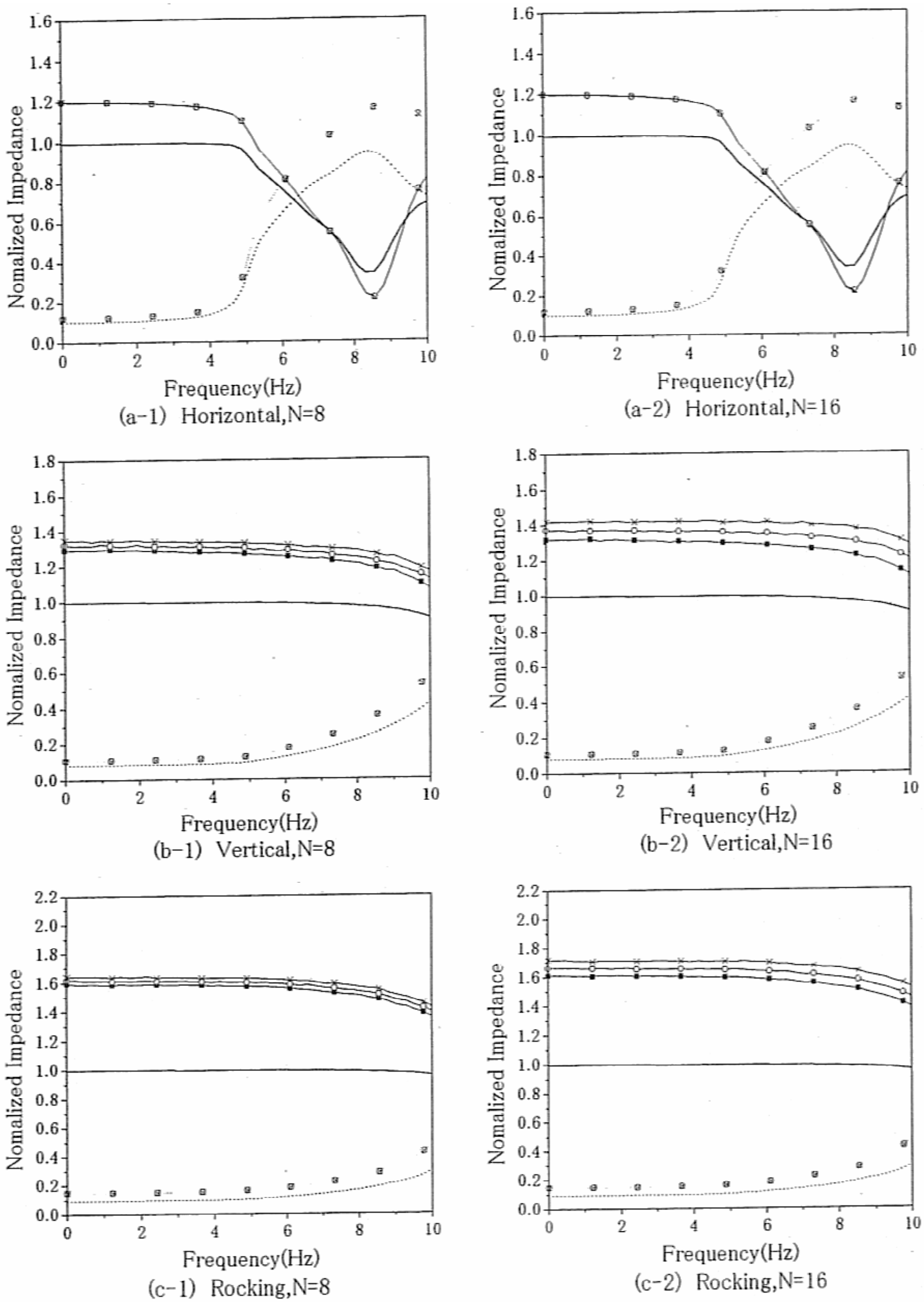


Fig.6 Dynamic stiffness of case30,case31,case32,case33 for 8 and 16 micropiles